Registration and Fusion of X-Ray and Ultrasound Images for As-Built Modeling

Grace A. Clark

EE/EETD, Systems and Decision Sciences Section

Jessie A. Jackson

EE/DSED, Signal/Image Processing and Control Group

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Disclaimer and Auspices Statements

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We Have an Interdisciplinary Team

- **Ed Kokko - (PI)   ME/MMED**
  Structural analysis, FEA
- **Diane Chinn - ME/NTED**
  NDE, material science
- **Grace Clark, EE/EETD**
  Image/signal processing, automatic target recognition (ATR), pattern recognition, neural computing, sensor data fusion, NDE
- **Dave Chambers - EE/DSED**
  Wave modeling, physics, signal processing
- **Jessie Jackson, EE/LED**
  Image Processing, NDE, Software expert
- **Harry Martz - Leader, Center for Nondestructive Characterization**
- **Rob Sharpe - Leader, Center for Computational Engineering**

Agenda

- Introduction and Problem Definition
- Controlled Experiments with a “Phantom” Part
- Registration of the CT and UT Images
- Experimental Results
  - Manual Registration
  - Fusion by Visual Inspection
- *Automatic* Target / Flaw Recognition and Sensor Fusion Approach for CT and UT Images
- Summary

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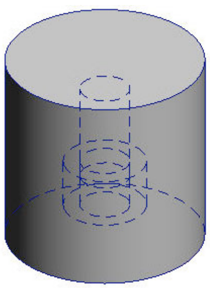
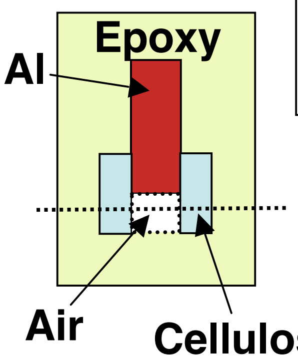
FY04 ME Techbase, "Process Development and Implementation of NDE-FEA Coupling for Numerical Analysis"

- *Created a RD&T Roadmap for Engineering Centers (CNDC and CCE)*
- *Multi-modal Sensor Fusion and Flaw Recognition for "As-Built Modeling"*
- *Processed X-Ray CT and Ultrasonic images from a known "phantom"*

Design Drawing





CAD Model

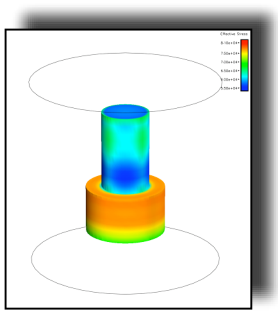
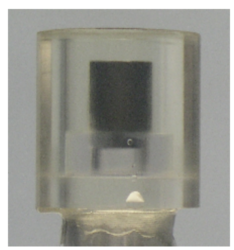
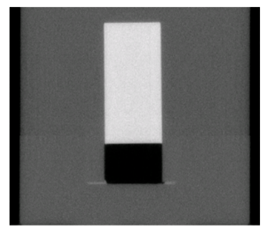


Photo of the Fabricated "Phantom"

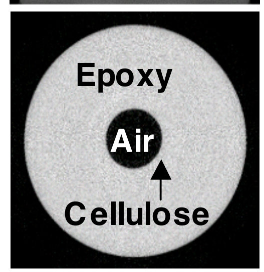


Horizontal Slice Depicted

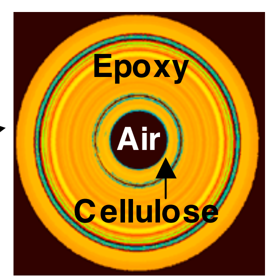
NDE Images



X-Ray CT Vertical Slice

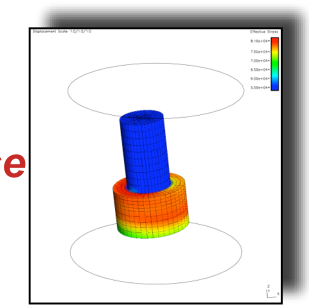


X-Ray CT Horiz. Slice: Epoxy-Cellulose Interface NOT Visible

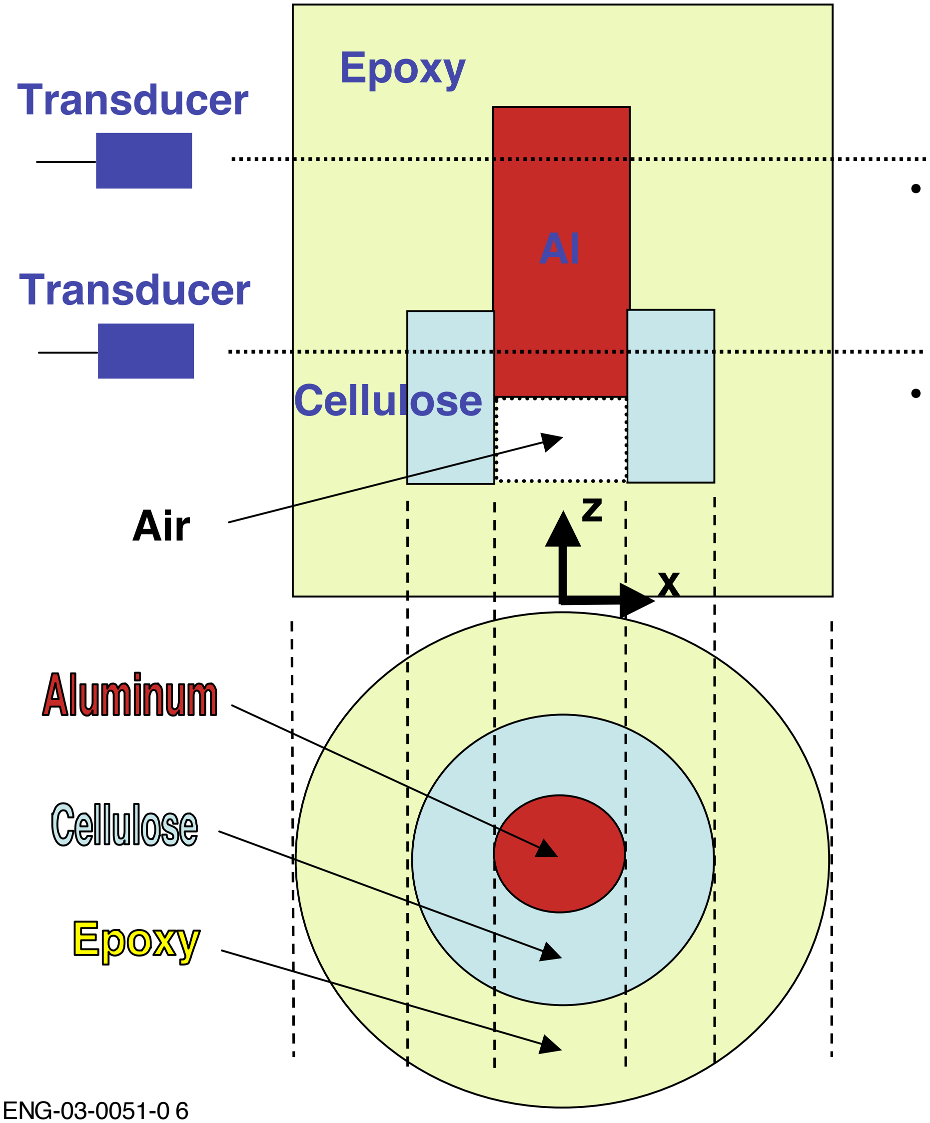


Ultrasonic Horizontal Slice: Epoxy-Cellulose Interface Visible

Finite Element Model



Our Test Part Consists of 3 Concentric Cylinders Made of Aluminum , Cellulose and Epoxy

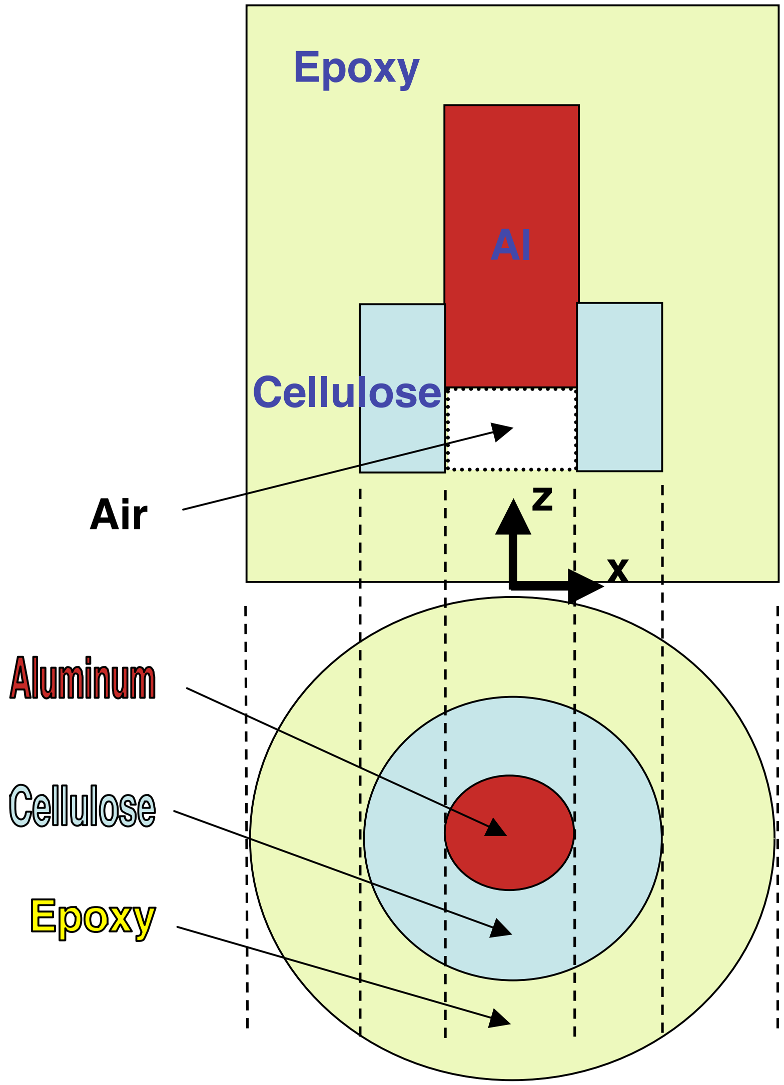


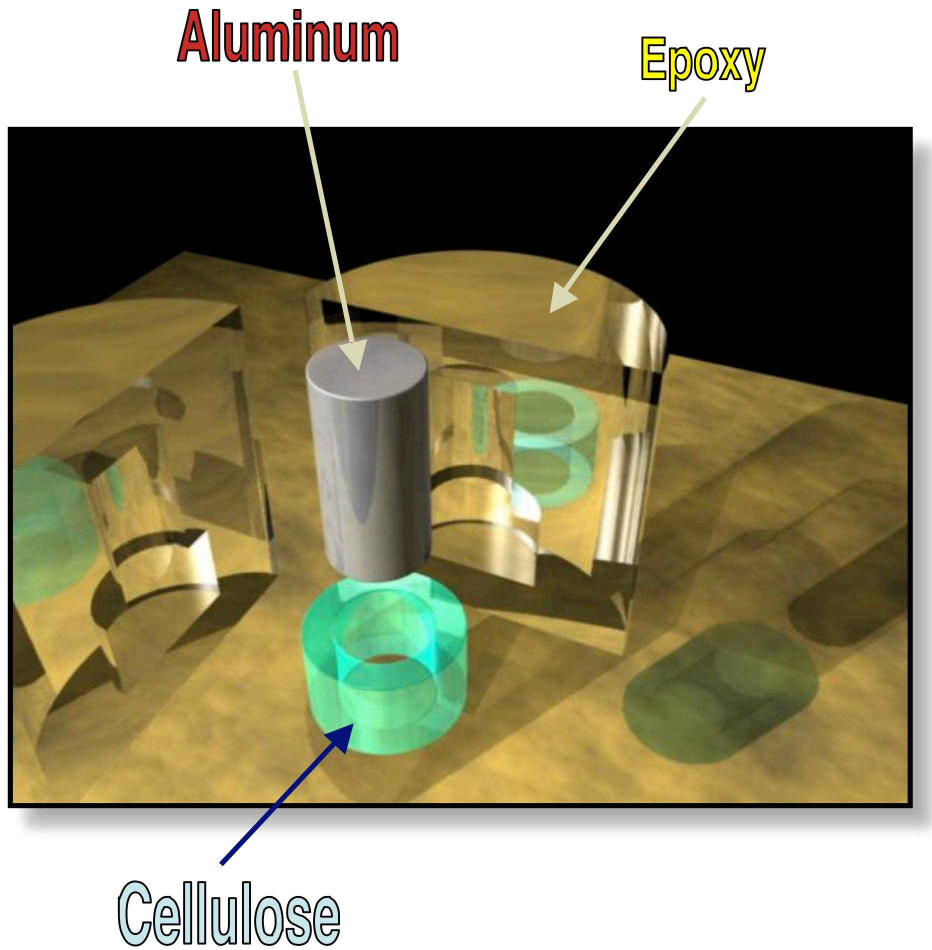
- Both X-Rays (CT) and Ultrasonic Waves (UT) are used to image the part
- The part is rotated about the axis of the concentric cylinders:

  UT: Sample one image each degree over 360 degrees

  CT: Sample one image at less than one degree over 360 degrees

Our Test Part Consists of 3 Concentric Cylinders Made of Aluminum , Cellulose and Epoxy





CT and UT Measure Different Material Properties. Each Modality Has Strengths and Weaknesses.

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CT (X-Rays)

Measures X-Ray Attenuation

$$A = f\left[E_A, \rho, Z\right]$$

where :

E_A = Energy Applied

ρ = Density

Z = Atomic Number (# protons)

Strengths:
- **A strong function of Z (~ Z^r)**
- **High spatial resolution (good for observing part geometry)**

Weaknesses:
- ***Not very sensitive to changes in density - Not good for detecting closed cracks***

UT (Ultrasonics)

Measures reflected acoustic energy

$$R = g\left[\rho, E\right]$$

where :

ρ = Density

E = Modulus of Elasticity

= Young's Modulus

Strengths:
- ***Good for detecting small changes in density and modulus***
- ***Good for detecting closed cracks***

Weaknesses:
- ***Low spatial resolution due to temporal "ringing" of band-limited ultrasonic transducers***

Two Image "Slices" Demonstrate the Strengths and Weaknesses of CT and UT

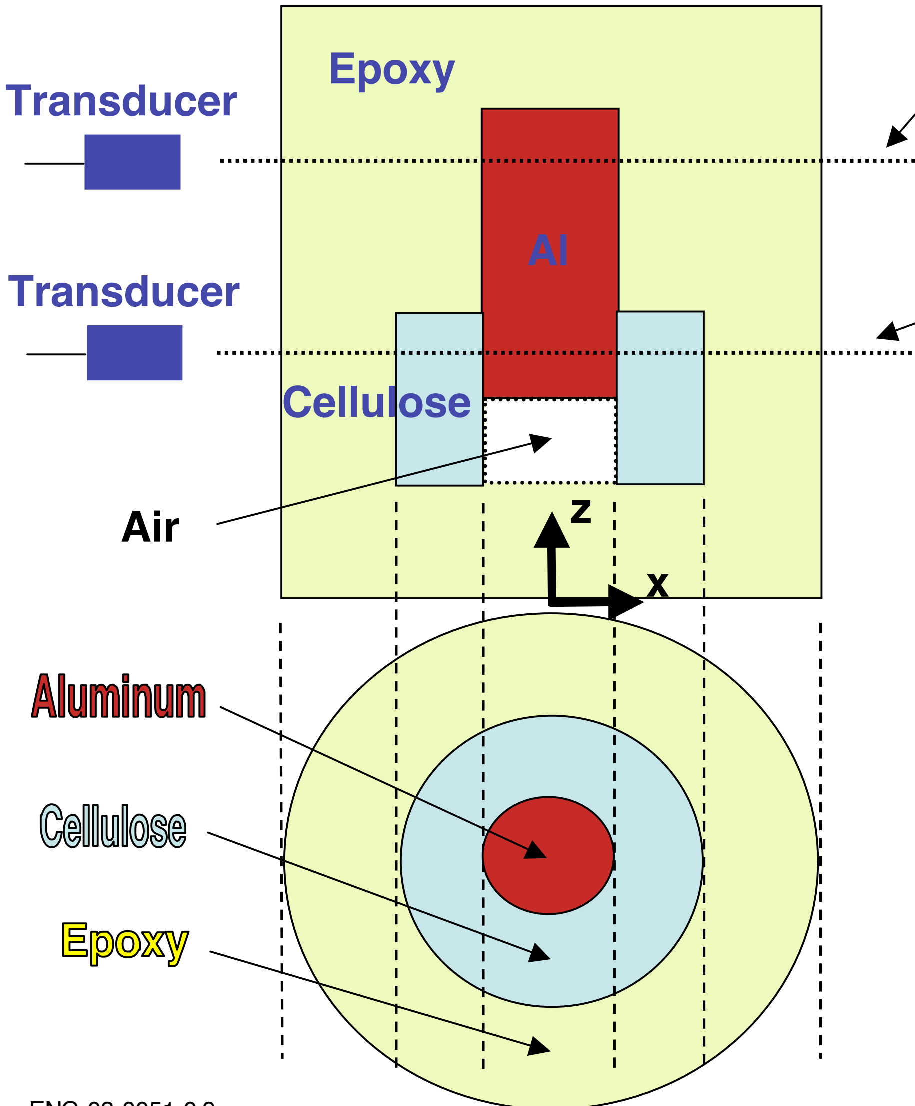


Image Slice 1:

- The aluminum-epoxy interface contrast is strong for both CT and UT

Image Slice 2:

- The *aluminum-cellulose* and *aluminum-epoxy* interface contrasts are strong for both CT and UT
- The air-cellulose and air-epoxy interface contrast is strong for both CT and UT
- The epoxy-cellulose interface contrast is: *Strong for UT, Weak for CT*

The Epoxy-Cellulose Interface Has Low Contrast With CT, but Much Higher Contrast With UT

The Epoxy - Cellulose Interface:

- **Epoxy and Cellulose have approximately the same density and modulus:**

Composition

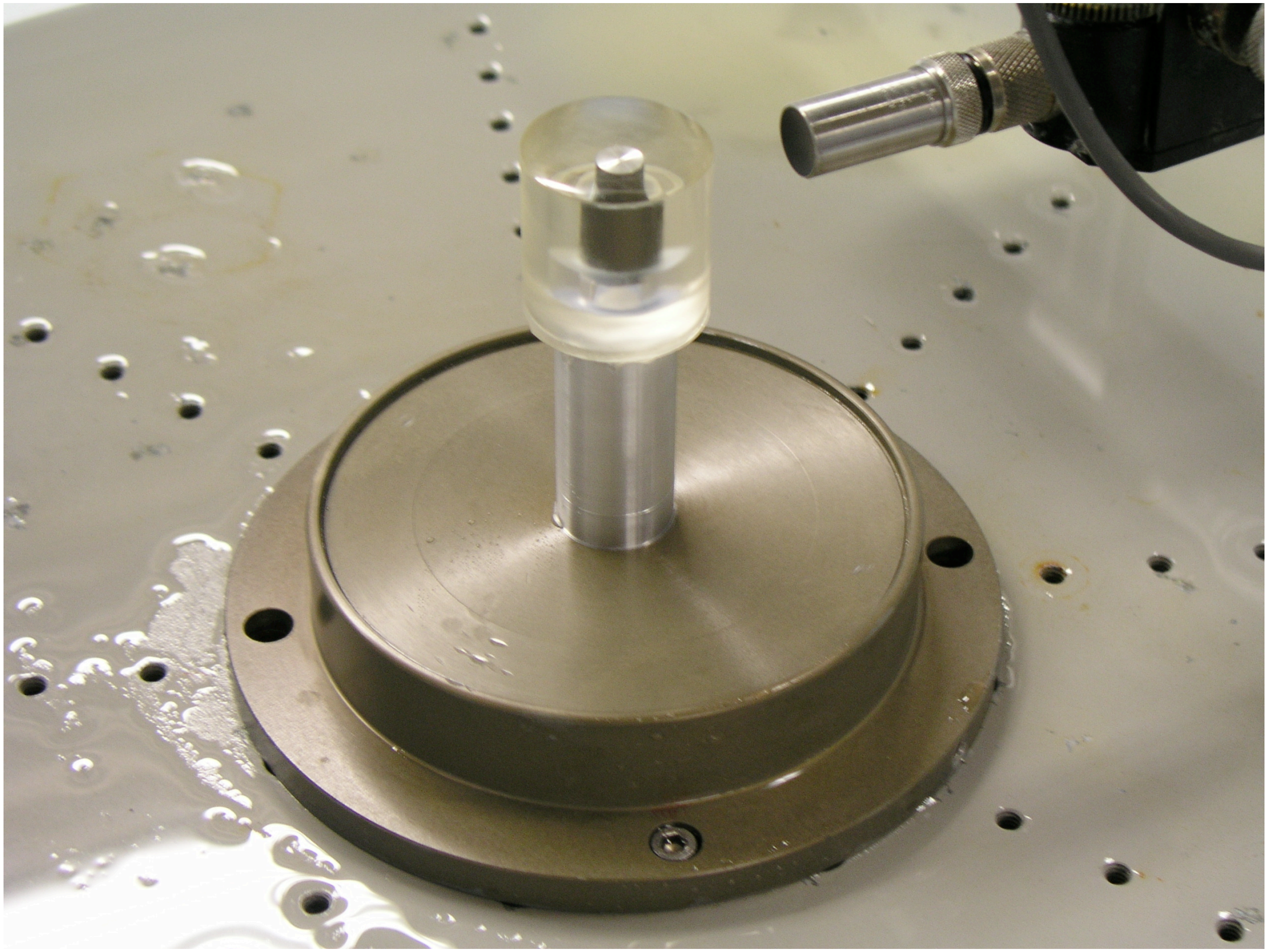
- **Density:** $\rho_{Epoxy} \approx \rho_{Cellulose}$
- **Coefficient of Elasticity: (Young's Modulus)** $E_{Epoxy} \approx E_{Cellulose}$
- **Atomic Number:** $Z^{eff}_{\;Epoxy} \approx Z^{eff}_{\;Cellulose}$

• UT can detect interfaces well

• CT is minimally effective for interface detection, good for geometry characterization

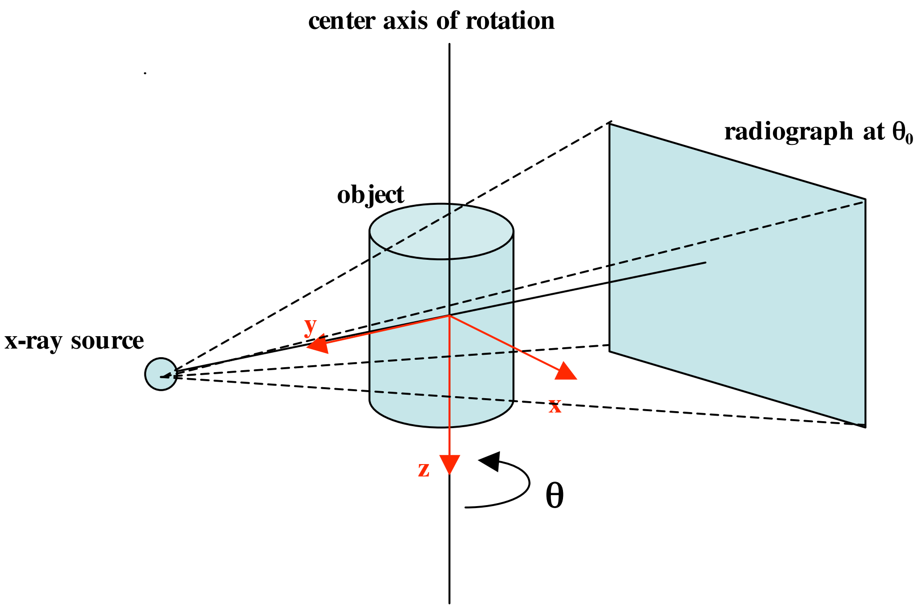
- **The other interface contrasts are strong for both CT and UT**

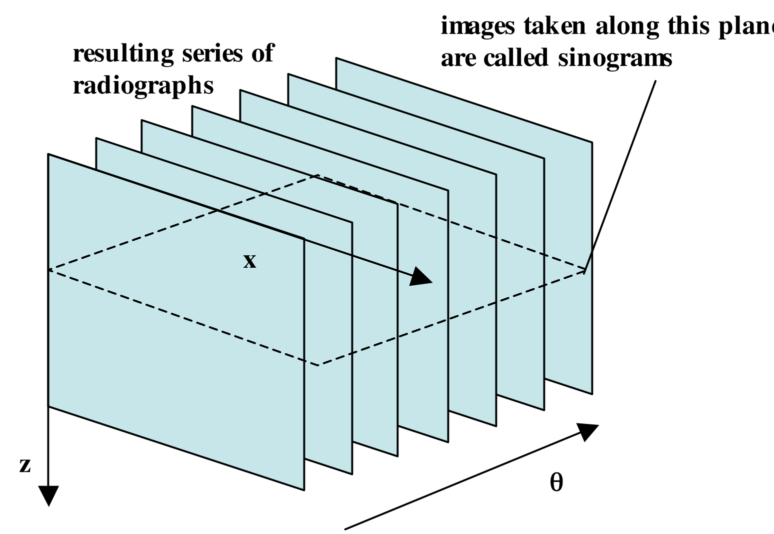
The "Phantom" Part is Placed on a Fixture And Rotated. The Transducer Position is Fixed



CT Image Acquisition

CT data are acquired in the form of a series of radiographs taken from different angles around the object. Although the object is actually physically rotated, in order to perform the reconstruction processing it is assumed that the x-ray source and radiograph system are rotated and the object is stationary with respect to the xyz coordinate system.





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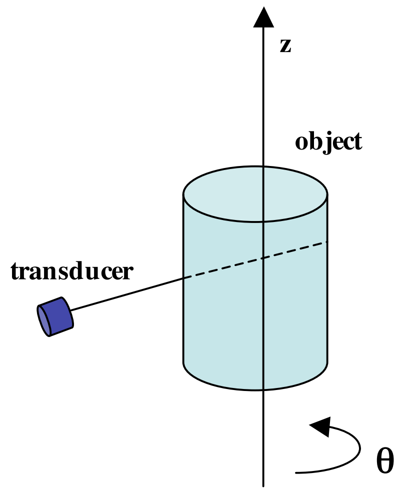
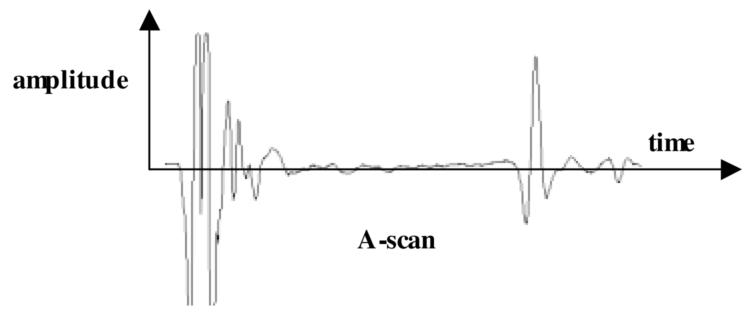
UT Image Acquisition

In UT processing the object is placed in water with an ultrasonic transducer a short distance from it. A signal is sent from the transducer towards the object and the reflected signal is acquired by the transducer. The transducer is rotated around the object in steps acquiring signals, it is then moved up and rotated again. Each signal that is acquired is called an A-scan.

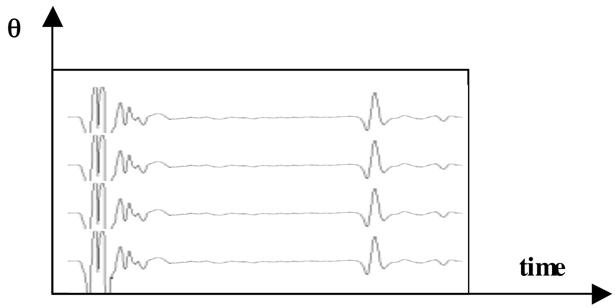
The signals are collected at a sampling rate Δt.

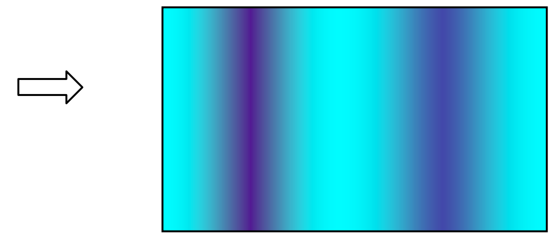




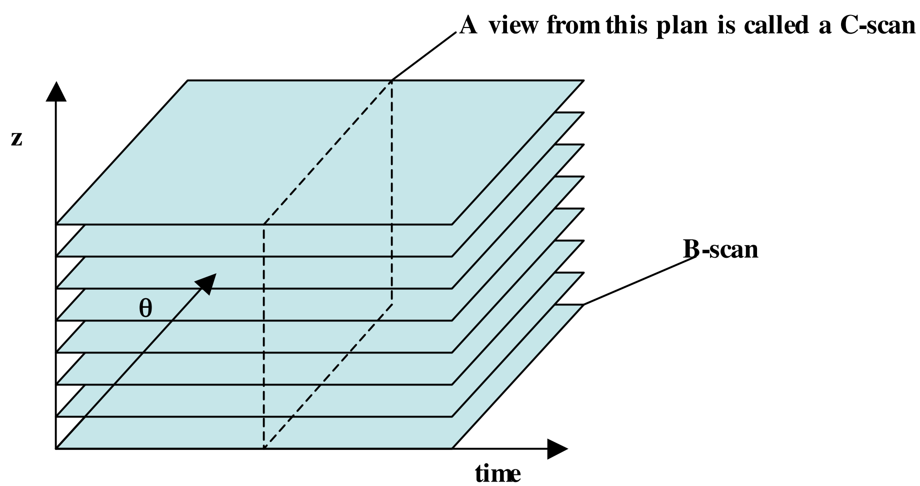
UT Acquisition (con't)

The collection of signals at a given z location is called a B-scan.





If a series of B-scans is stacked, an image of a plane cut through the stack is along the time axis called a C-scan.



UT Image Formation and *CT/UT Image Co-Registration* Require an *Iterative* Process

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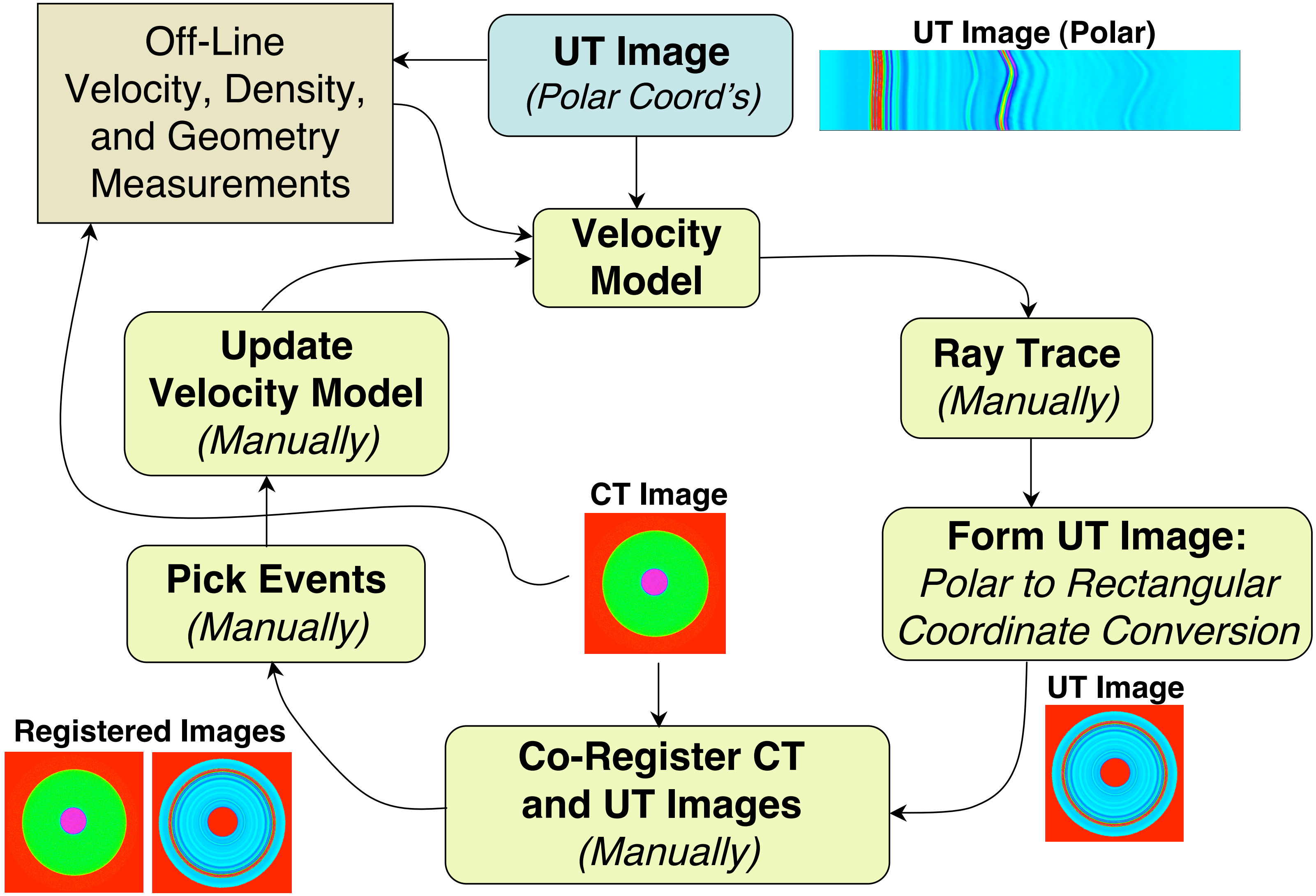


Ray Tracing Requires Knowledge of the Material Properties *(Density, Velocity)*

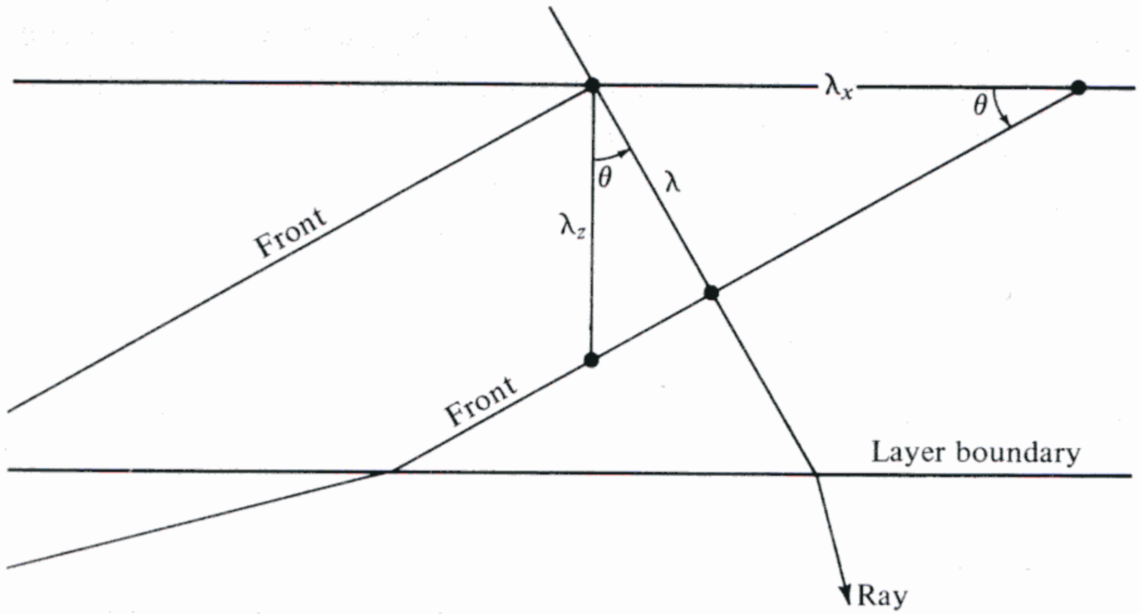
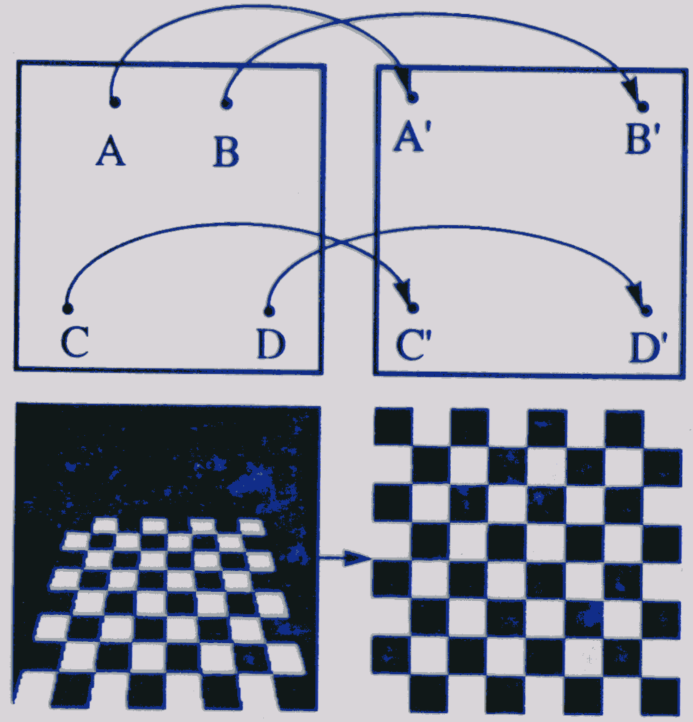


FIGURE 9–1
Rays and wavefronts in a layer. The wavelength λ_x seen on the x axis and the wavelength λ_z seen on the z axis are both greater than the wavelength λ seen along the ray. Clearly, $\lambda/\lambda_x = \sin\theta$ and $\lambda/\lambda_z = \cos\theta$ so the spatial frequencies $k_x = 2\pi/\lambda_x$ and $k_z = 2\pi/\lambda_z$ satisfy $k_x{}^2 + k_z{}^2 = (2\pi/\lambda)^2 = \omega^2/v^2$, which, besides being the pythagorean theorem (since $\sin\theta = k_x v/\omega$), is the Fourier transform of the wave equation. Snell's law that $(\sin\theta)/v$ is the same from layer to layer is thus equivalent to saying that k_x/ω is the same in each layer. That the spatial frequency k_x is the same constant in each layer is essential to the satisfaction of continuity conditions at the layer interfaces.

Image Co-Registration: A Perspective Transformation Can Correct for Perspective, Rotation and Scale

Objective: Geometrically transform an image to map four or more control points to their desired coordinates. Assume perspective correction for intermediate

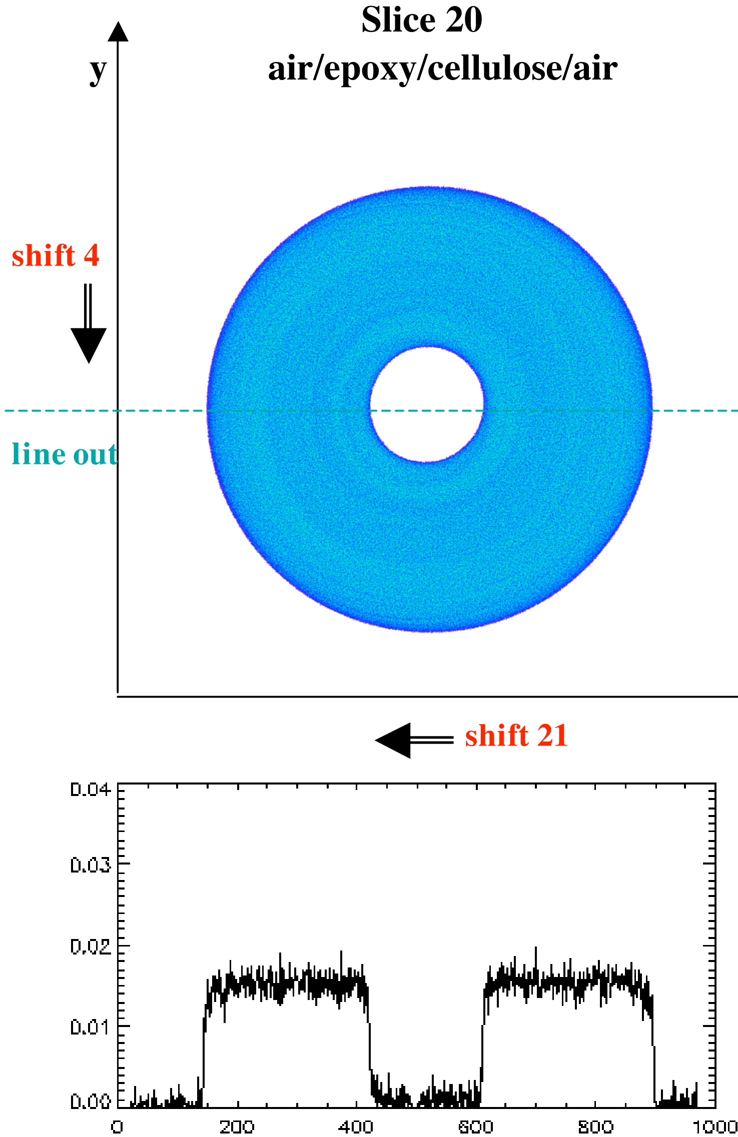


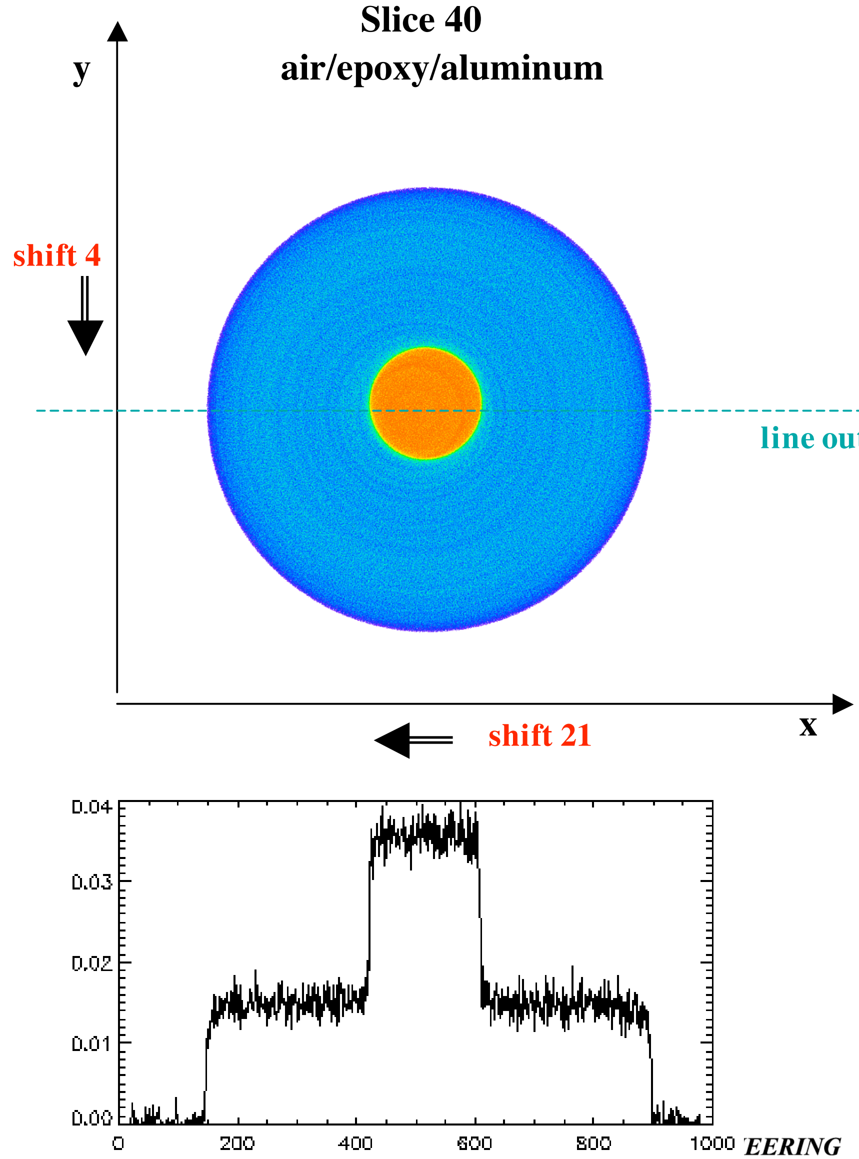
Method:
- Select four or more control points.
- Compute 3x3 coordinate transformation matrix.
- At each point in the output image, calculate corresponding coordinates in the input image, then interpolate pixel value based on four nearest neighbors in the input image.

CT - Original

Size - 999 x 999
object is not centered
epoxy/cellulose boundary can not be seen

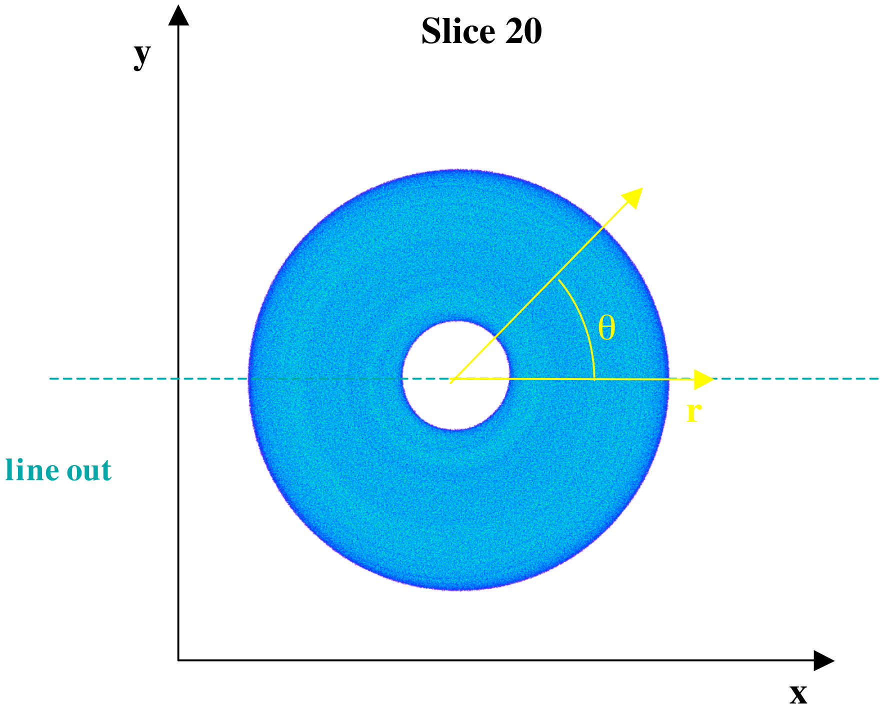
manually determine amount to shift in order to center object

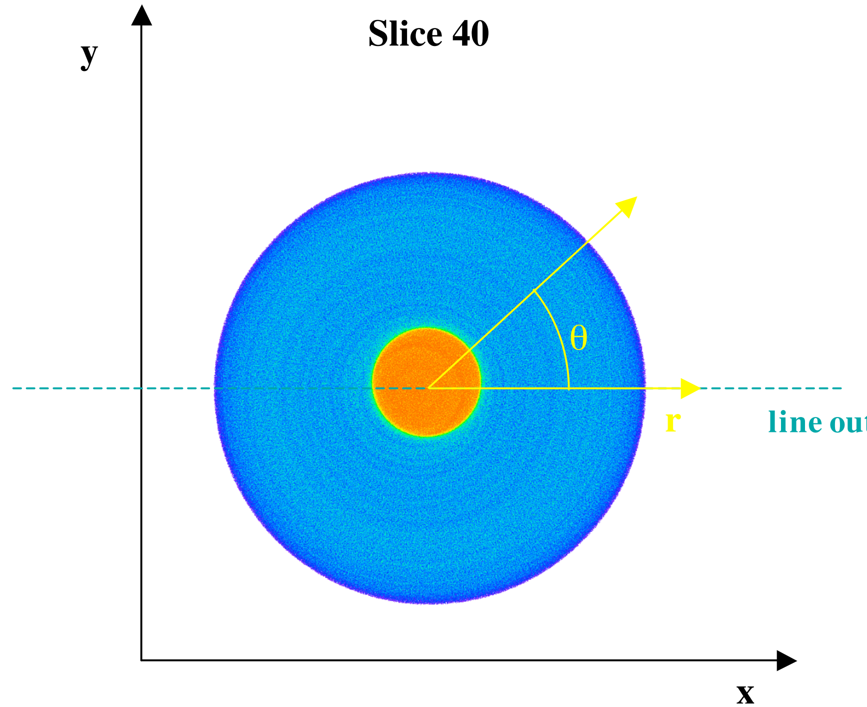


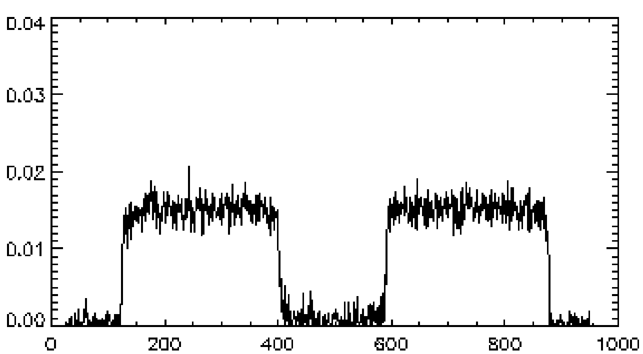


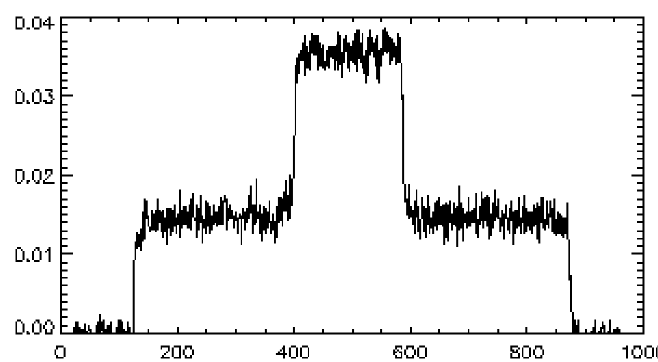
CT - Shifted and Resized

Size - 1000 x 1000



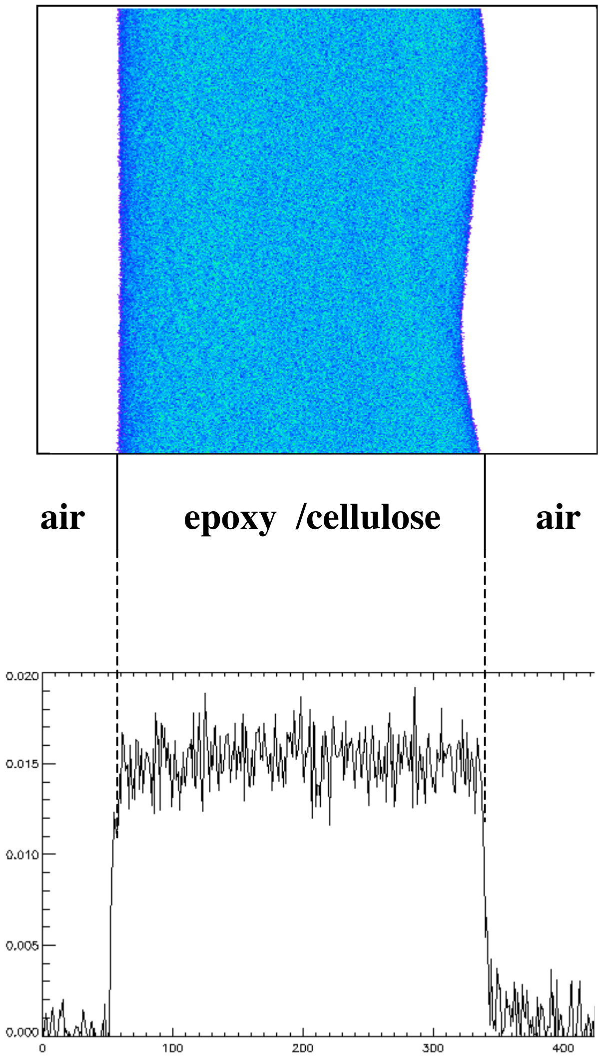


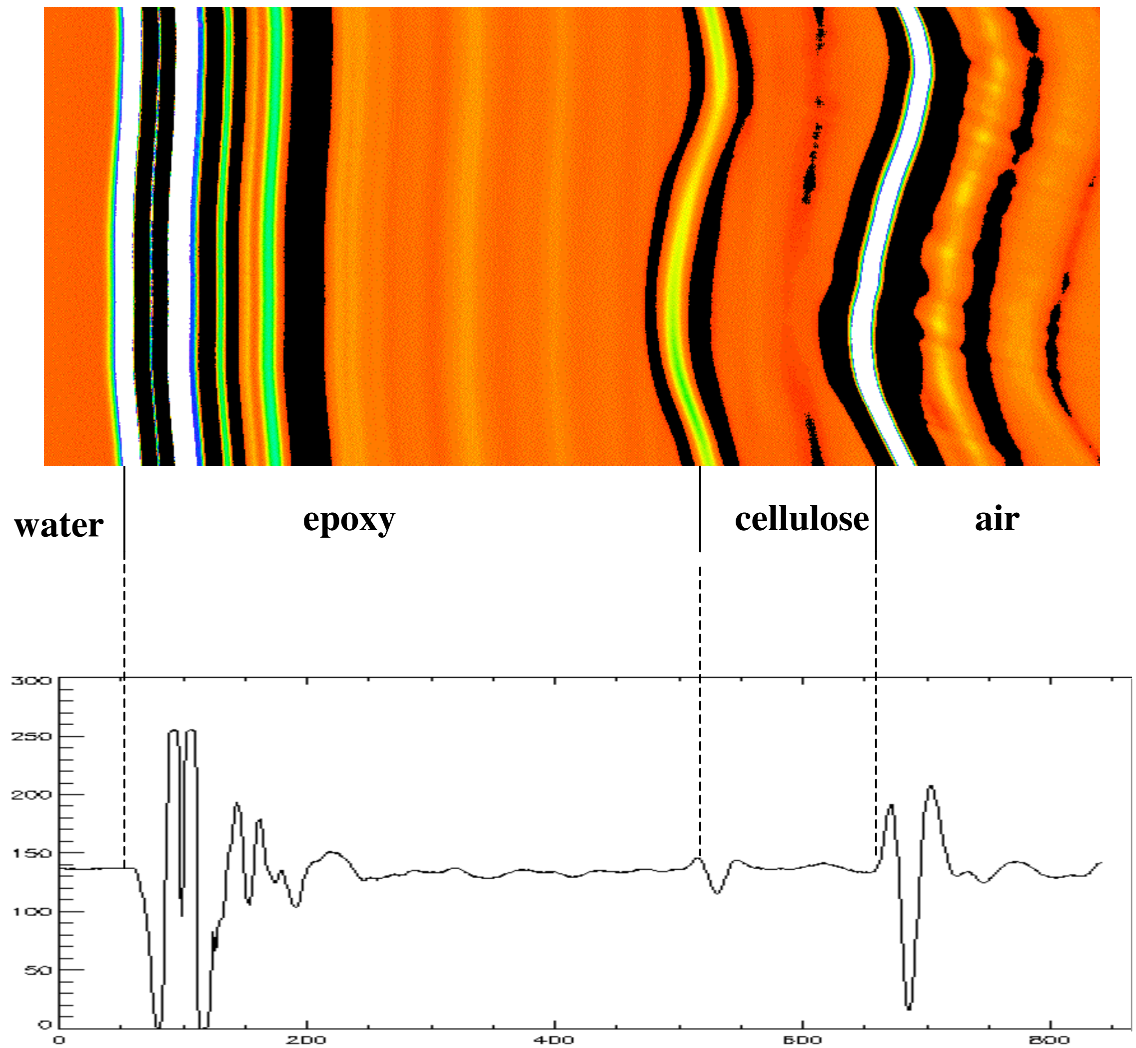




Slice 20

CT | UT





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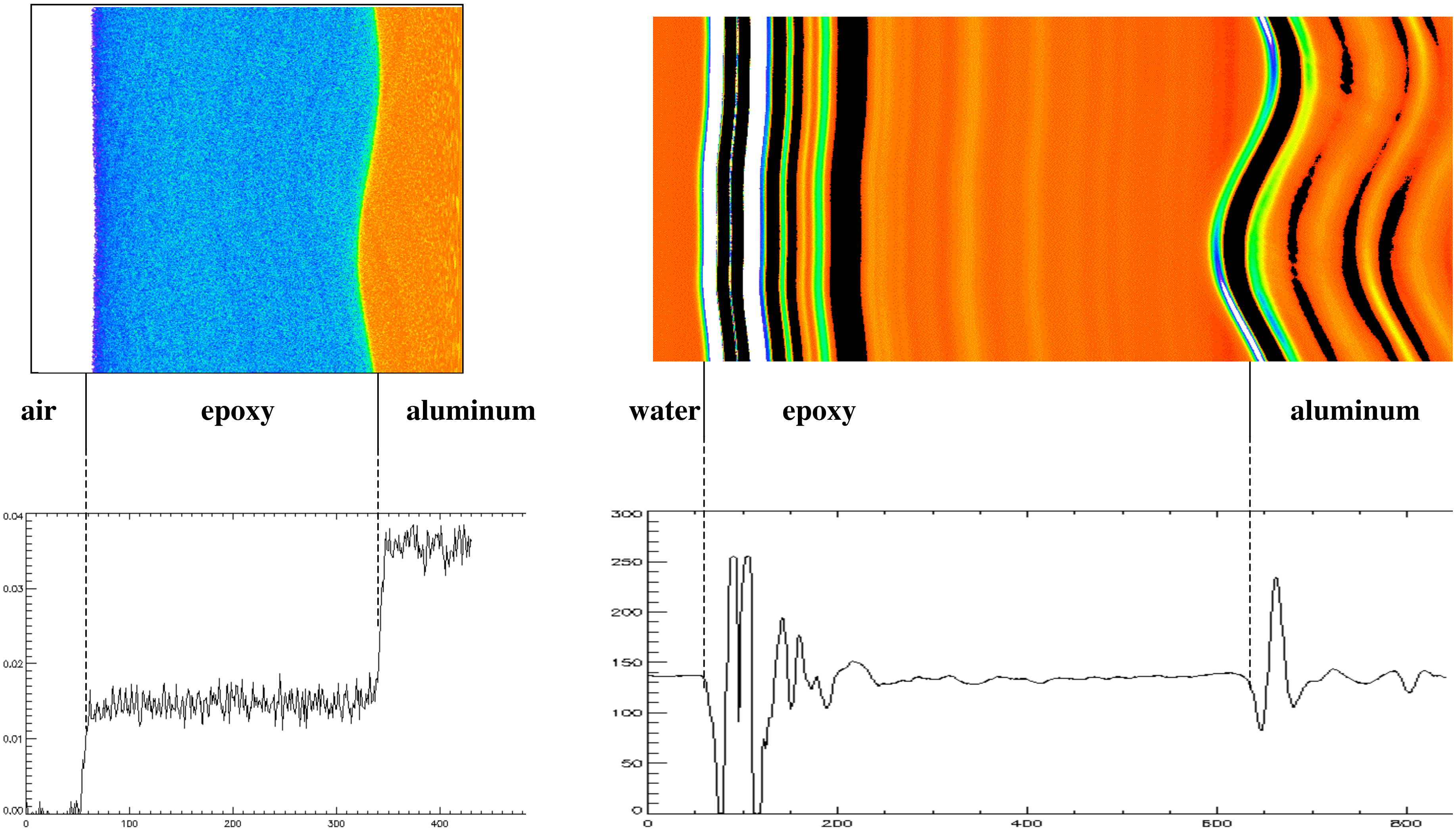
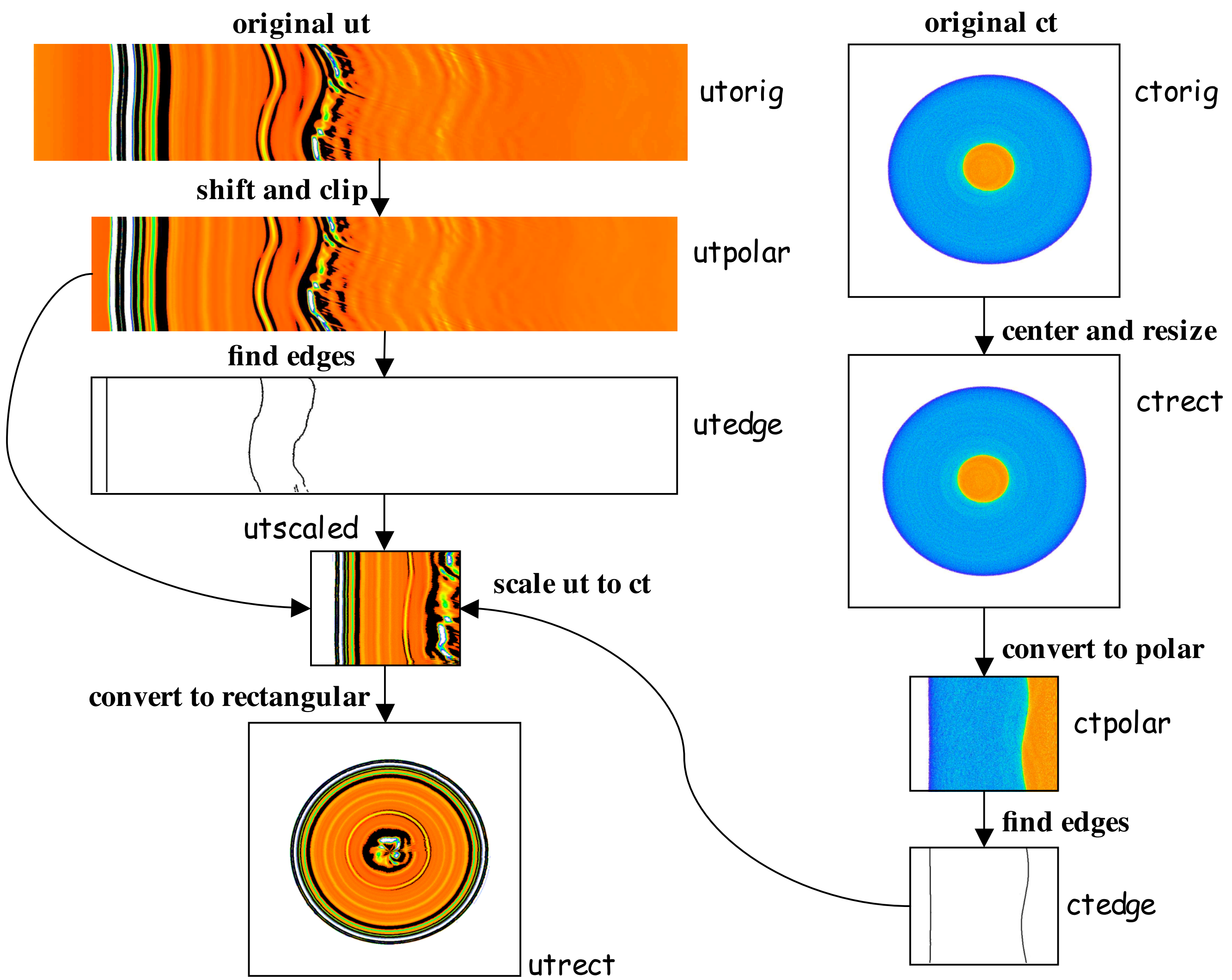
Slice 40

CT UT

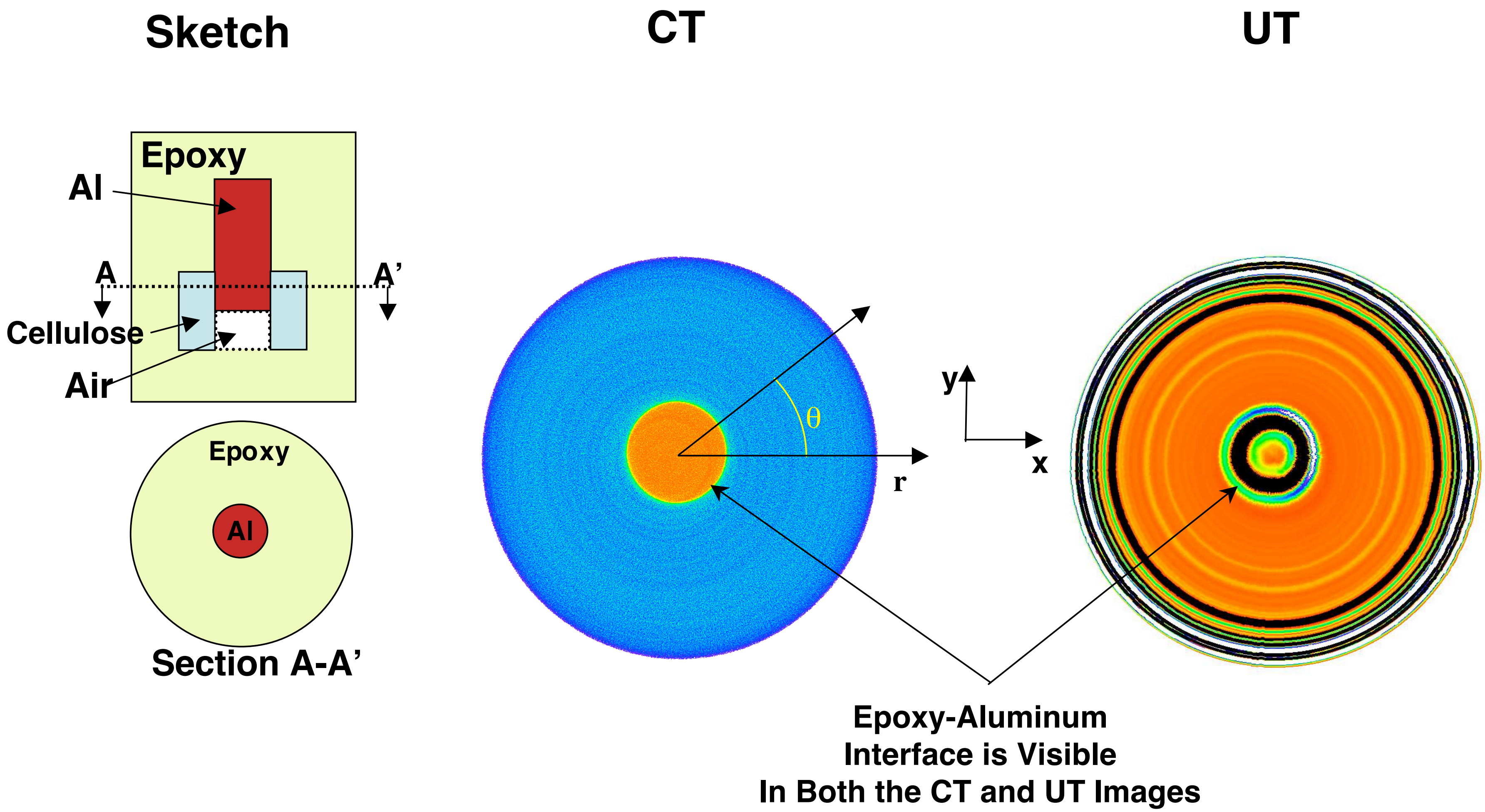


A *Manual* Iterative Process Was Used For CT/UT Image Formation and Registration: Epoxy/Cellulose/Aluminum Slice



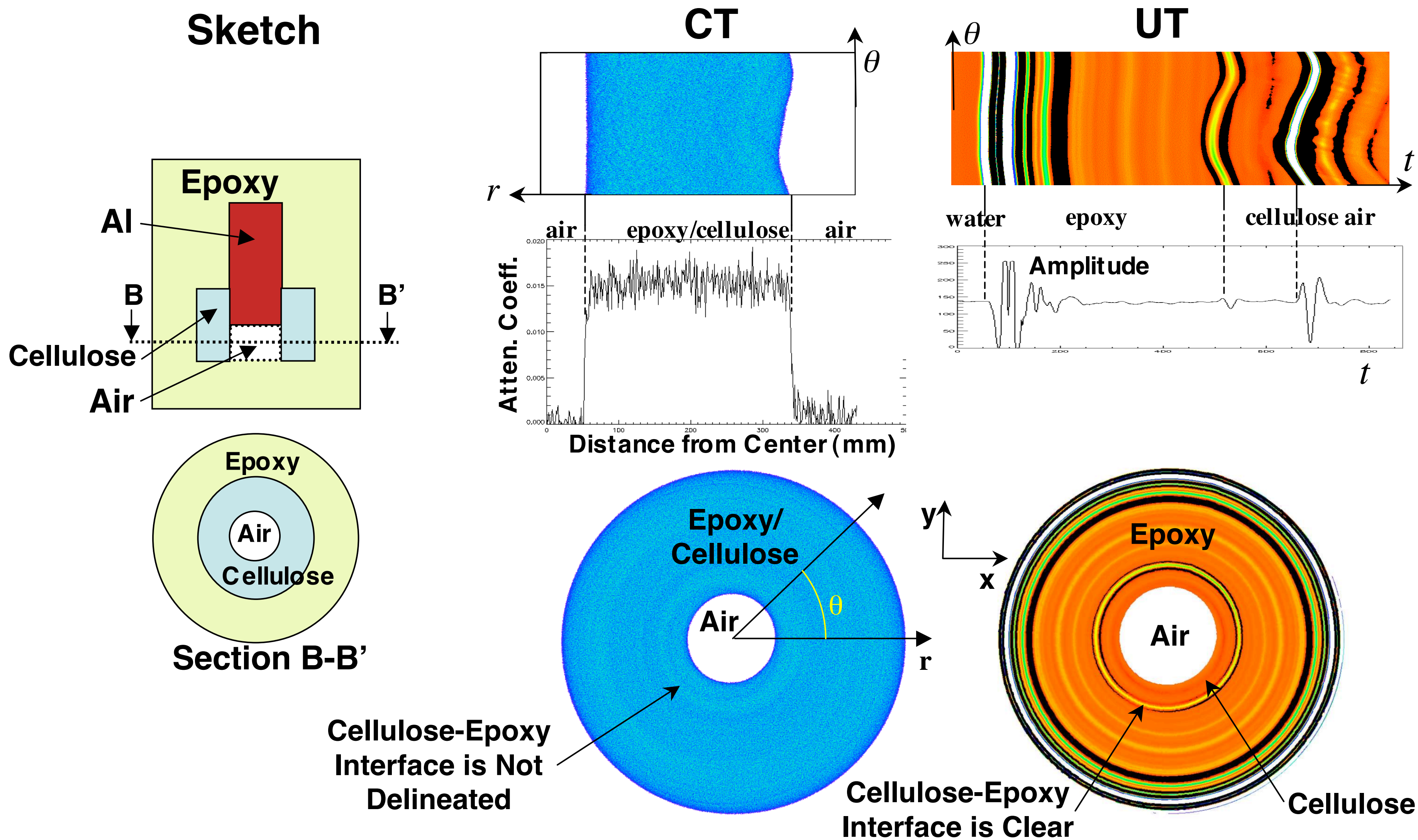
Summary of Horizontal Slice 40: Epoxy and Aluminum

Both CT and UT Show the Epoxy-Al Interface

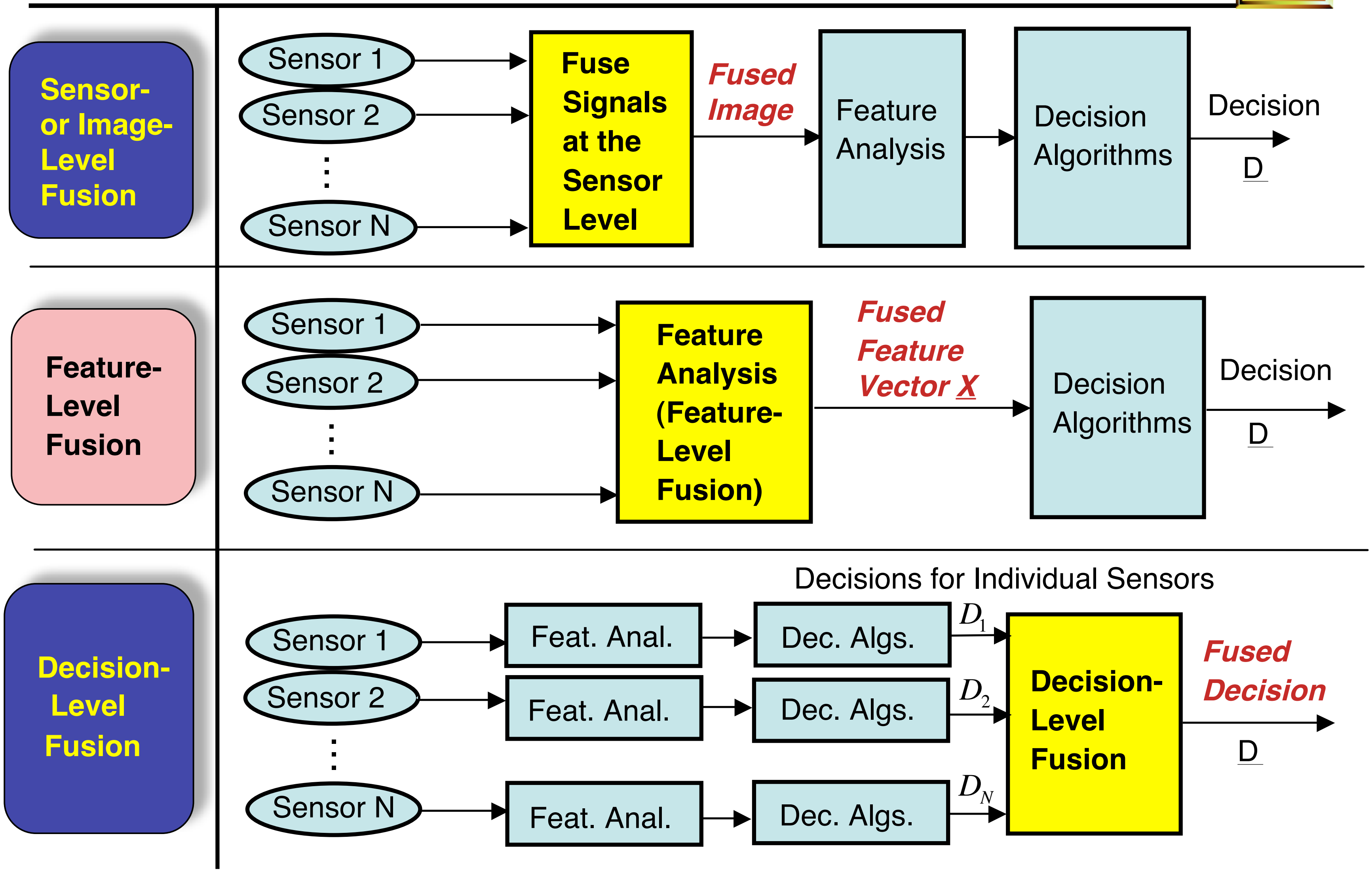


Summary of Horizontal Slice 20: Epoxy, Cellulose, Air

Cellulose-Epoxy Interface is Visible Only in the UT Image



Information Is Generally Fused at One or More of Three Basic "Levels" in the Processing Scheme



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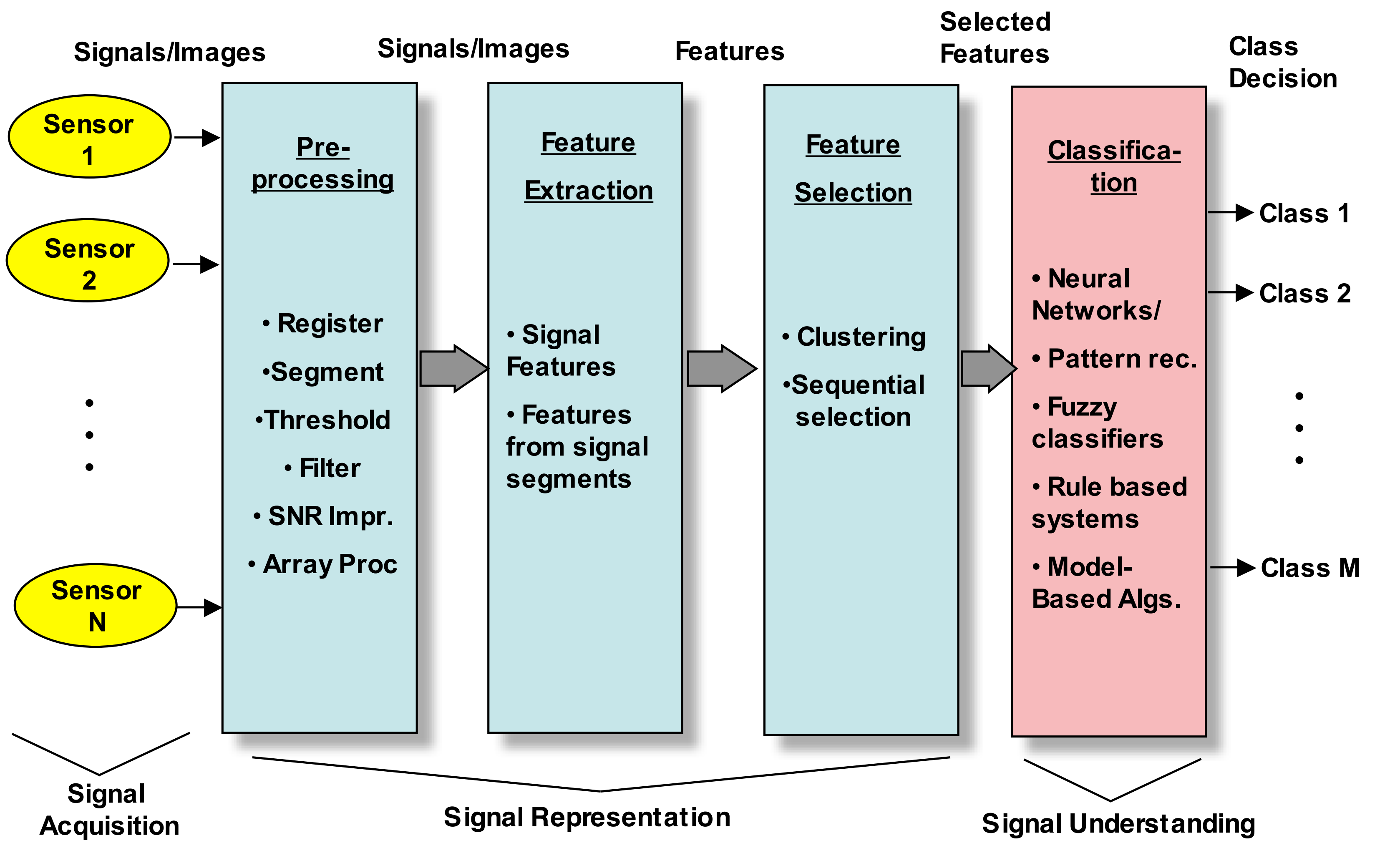
Target / Flaw Recognition Depends Heavily on the Judicious Choice of Signal / Image Features



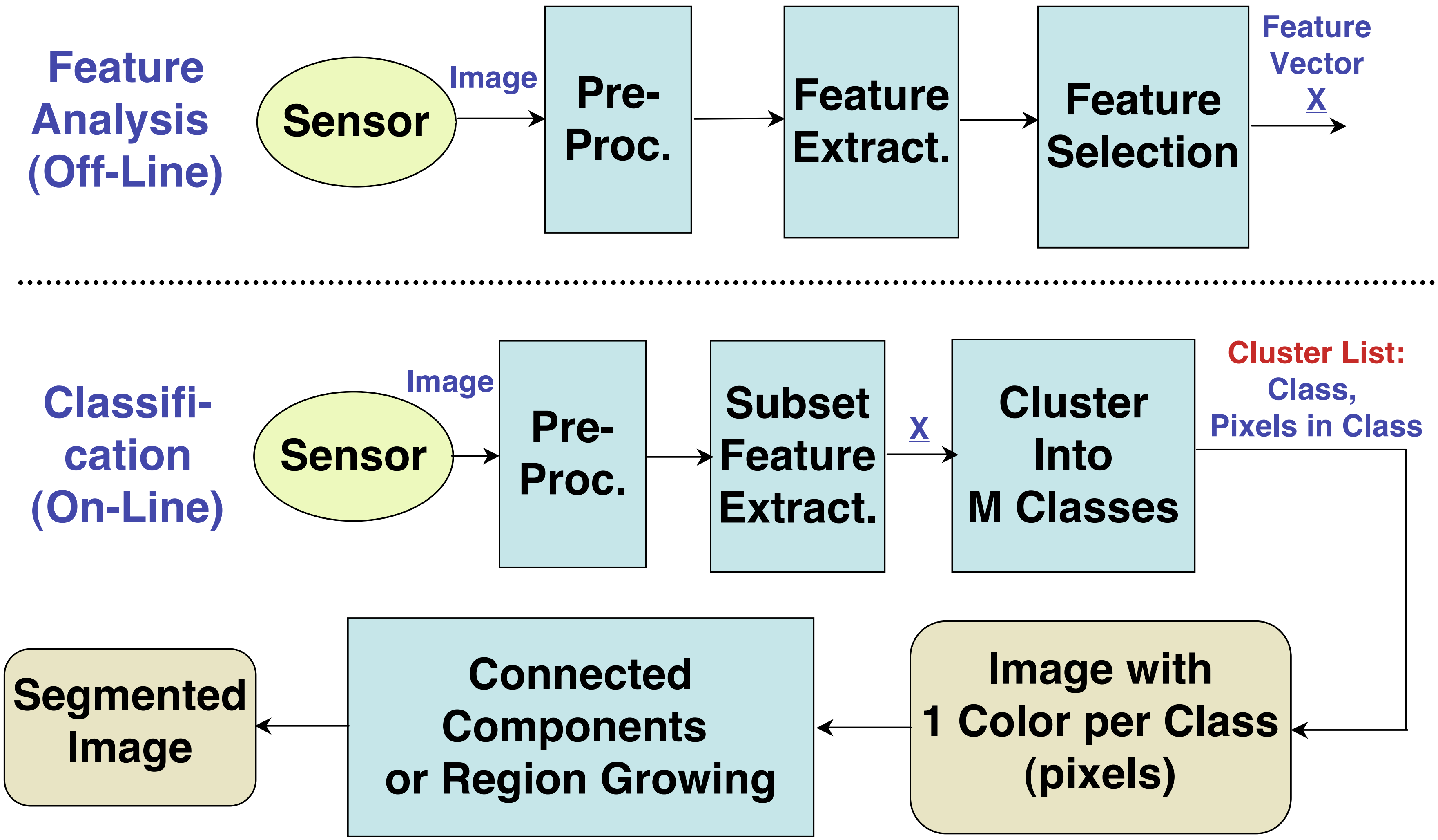
Technical Approach *(Driven by Programmatic Needs):* We Propose R&D to Attack Several Key Problems

- Feature Analysis (the most important aspect of target recognition - the key to separating events from clutter/noise)
  - Feature extraction (advanced features to calculate)
  - Feature selection (optimal selection of the feature subset from the full set)

- Fusion of images having different resolutions (e.g. CT and UT images of the same scene)
  - Image sharpening
  - Superresolution

- Registration of multiple images from multiple sensors
  - When fiducial markers are available
  - When fiducial markers are not available (a common and difficult problem)

For a Single Sensor Type (Modality), We Can Process as Follows:



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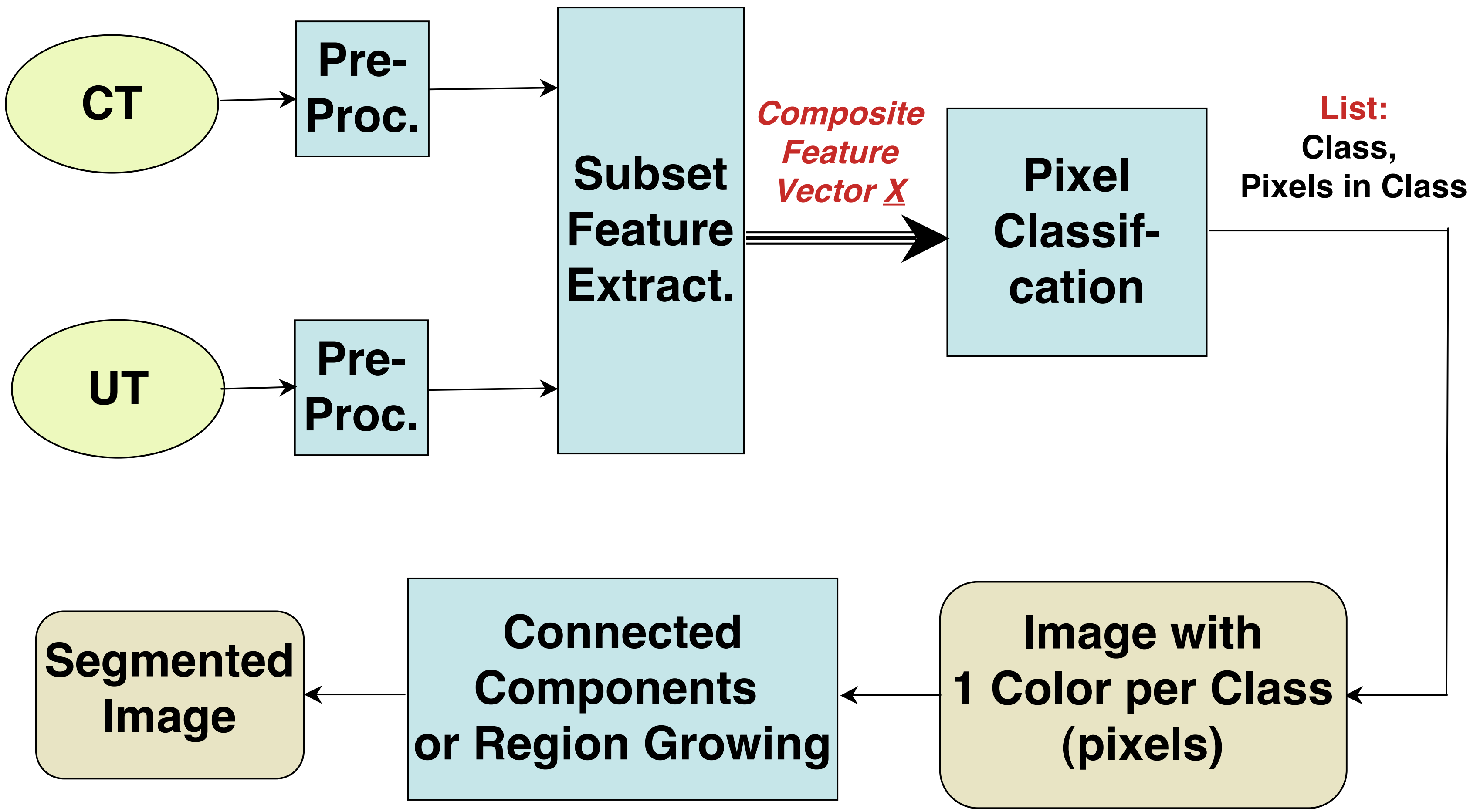
In the Near-Term, We Are Using *Feature-Level Fusion* for CT/UT Images



Spatial Resolution Enhancement and *Fusion* Can Improve *All Aspects* of NDE Processing

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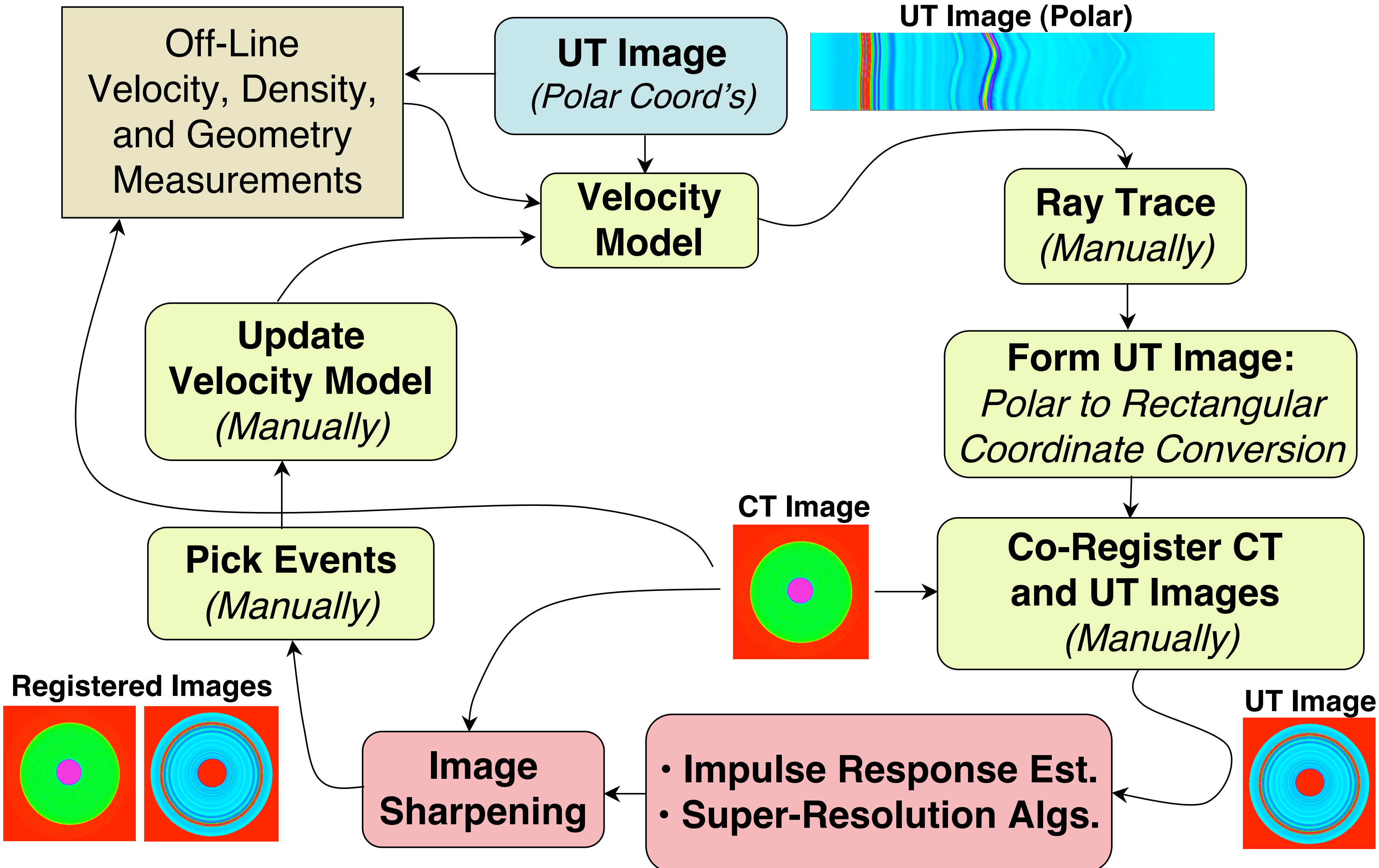

Summary

- **Work in progress**

- **The image formation (reconstruction) process and the registration process are coupled**

- **We have preliminary results for CT and UT Fusion**
  - **Controlled Experiments with a "Phantom Part"**
  - **Manual registration of images**
  - **Fusion by visual inspection**

- **Ongoing Work**
  - **Automatic registration of images**
  - **Automatic target / flaw recognition and sensor fusion**